

A STUDY ON THERMOFORMING PROCESS OF STRETCHABLE CIRCUIT AND ITS PERFORMANCE IN MANUFACTURING OF AUTOMOTIVE LIGHTING

MOHAMAD FIKRI BIN MOHD SHARIF

UNIVERSITI SAINS MALAYSIA

2018

**A STUDY ON THERMOFORMING PROCESS OF STRETCHABLE
CIRCUIT AND ITS PERFORMANCE IN MANUFACTURING OF
AUTOMOTIVE LIGHTING**

by

MOHAMAD FIKRI BIN MOHD SHARIF

**Thesis submitted in fulfilment of the
requirements for the Degree of
Master of Science**

April 2018

ACKNOWLEDGEMENTS

Praise is exclusively to Allah. The Lord of the Universe and Peace is upon the Master of the Messengers, his family and companions.

Firstly, I would like to express deepest appreciations to my lovely parents: Mohd Sharif and Mek Jah, and my siblings for their prayers and continuous support throughout my life. A special thank also to Collaborative Research in Engineering, Science & Technology Centre (CREST) for providing grant P24C1-2015 to support my research which covers material expenses, my allowance and tuition fees.

I express my special thanks and gratitude to my supervisor Dr. Abdullah Aziz Saad and co-supervisor Dr. Khalil Abdullah for their patience, guidance, encouragement, support and valuable information during my research. Not to forget Jabil ETS Department and members, Mr. Zambri Samsudin, Mr. Fakhrozi Che Ani, Mr. Lai Ming and Mr. Yusuf Tura Ali for their supports and providing me equipment and machine to conduct my experiment.

My special thanks are also to the Dean, Prof. Dr. Zainal Alimuddin Zainal Alauddin and Vibration Lab members, Mr. Wan Amri, Izuddin Alisah and Nabil for their contributions in the preparation of vibration test setup apparatus. Thanks also to Mr. Fakruruzi for giving idea to run pulling test using universal testing machine (UTM). I gratefully appreciate USM for providing me research study platform which help me a lot improve my knowledge.

Mohamad Fikri Bin Mohd Sharif

April 2018

TABLE OF CONTENTS

	Page
ACKNOWLEDGEMENTS	ii
TABLE OF CONTENTS	iii
LIST OF TABLES	vii
LIST OF FIGURES	viii
LIST OF ABBREVIATION	xii
ABSTRAK	xiv
ABSTRACT	xvi
CHAPTER ONE: INTRODUCTION	
1.1 Background	1
1.2 Problem Statement	2
1.3 Objective of Research	3
1.4 Scope of Research Work	3
1.5 Thesis Organisation	4
CHAPTER TWO: LITERATURE REVIEW	
2.1 Introduction	5
2.2 Evolution of Circuit Design	5
2.2.1 Printed Circuit Board (PCB)	6
2.2.2 Flexible Circuit	7
2.2.3 Moulded Interconnect Devices (MID)	8

2.3	Stretchable Circuit	10
2.3.1	Trace Design	10
2.3.2	Substrate Material	11
2.3.3	Curing and Sintering Processes of Conductive Ink	12
2.3.4	Interconnect Material and Processing	14
2.5	Polymeric Substrate Characterisation	16
2.6	Circuit Printing Technique	17
2.7	Parameters That Affect Final Product of Thermoforming Process	20
2.8	Application of Stretchable Circuit in Thermoforming Process	23
2.9	Interconnect Material Testing	24
2.10	LED Lighting Evaluation	25
2.11	Finite Element Simulation of Thermoforming Process	26
2.12	Summary	27

CHAPTER THREE: METHODOLOGY

3.1	Overview	29
3.2	Printing Process	30
3.2.1	Screen Mesh Fabrication	30
3.2.2	Conductive Ink Preparation	31
3.2.3	Printing and Curing Processes of Ink	31
3.3	Thermoforming Process Preparations	32
3.3.1	Mould Fabrication	32
3.3.2	Thermoplastic Substrate Selection	33
3.3.3	Thermoforming and Trimming Processes	34
3.4	Dimensional and Thickness Measurements of Substrate	36

3.5	LEDs Assembly on Circuit	37
3.6	Electrical Performance Measurement	39
3.6.1	Resistance and Sheet Resistance of Circuit Traces	39
3.6.2	Voltage, Current, Resistance and Power Consumption	41
3.6.3	LEDs Lighting	43
3.7	Mechanical Performance Measurement	44
3.7.1	Scanning Electron Microscopy (SEM) Analysis of Circuit	44
3.7.2	LED Joint Strength	45
3.7.3	Vibration Loading	45
3.8	Finite Element Simulation of Thermoforming Process	46
3.9	Summary	50

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1	Overview	51
4.2	DSC Analysis for Substrate Material Selection	51
4.3	Thermoforming Product Analysis	54
4.4	Electrical Performance	63
4.4.1	Resistance and Sheet Resistance Results of Circuit Trace	63
4.4.2	Voltage, Current, Resistance and power Consumption	67
4.4.3	LEDs Lighting Evaluation Results	69
4.5	Mechanical Performance	70
4.5.1	Microscopy Analysis of Silver Particles Distribution	70
4.5.2	LED Joint Strength	74
4.5.3	Vibration Test	76
4.6	Finite Element Analysis of Thermoforming Product	81

4.7	Summary	85
-----	---------	----

CHAPTER FIVE: CONCLUSION AND FUTURE WORK

5.1	Conclusion	88
5.2	Recommendation and Suggestion for Future Work	90

REFERENCES	91
-------------------	----

APPENDICES

LIST OF PUBLICATIONS

LIST OF TABLES

	Page
2.1 PCB to component area ratio (Leonida, 1989)	6
3.1 Viscosity and relaxation time for integral viscoelastic material	50
4.1 Comparison of stretch percentage of the substrate without stretchable ink and the substrate with stretchable ink	57
4.2 Thickness of top surface of thermoforming product	60
4.3 Substrate extension and thickness at wall surfaces of the thermoforming product	61
4.4 Resistances of the traces before and after the thermoforming process	64
4.5 Resistance readings at each corner area	65
4.6 Sheet resistance of the circuit before and after the thermoforming process	66
4.7 Electrical performance for each sample	68
4.8 Pull test results for each build matrix	75
4.9 Comparison between simulation and experiment of ASR and thickness	84

LIST OF FIGURES

	Page
2.1 Assembly principles of THT and SMT (Coombs, 2008)	6
2.2 Materials configuration of flexible circuit (Macleod, 2002)	8
2.3 Diffusing path between two contacting particles in conductive ink (Greer and Street, 2007)	13
2.4 Schematic illustration of (a) ACA (b) ICA in flip-chip bonding (Liu, 1999)	15
2.5 A detailed screen printing process (Lewis and Ry, 2010)	19
2.6 Parts formed by plug mould (left) and cavity mould (right) (Klein, 2009)	21
2.7 Thickness distribution of part cross section formed by cavity mould (Klein, 2009)	21
2.8 Thickness distribution of part cross section formed by plug mould (Klein, 2009)	22
3.1 Flow chart for the overall study	29
3.2 Drawing of the circuit using overlapping technique	30
3.3 Printing setup of the conductive ink using printing machine	32
3.4 (a) The original design of the automotive lighting (b) 3-D drawing of the original design and (c) fabricated mould for thermoforming process	33
3.5 Schematic diagram of DSC analyser	34
3.6 The modified thermoforming machine with the heater layout	35

3.7	(a) Heating process of the polycarbonate sheet and (b) movement of the mould and the plug to deform the sheet with vacuum pressure assist	35
3.8	Printed grid lines on the polycarbonate sheet	37
3.9	Top surface and wall surface locations of the thermoforming product	37
3.10	The building of (a) 1 st (b) 2 nd (c) 3 rd (d) 4 th and (e) 5 th matrices	38
3.11	(a) The actual LEDs arrangement and position on the new design automotive lighting and (b) schematic diagram of the LEDs arrangement in the circuit	39
3.12	The resistance and sheet resistance measurements at specified traces and the point locations throughout the circuit	40
3.13	New design automotive lighting connection to the power supply with LEDs' driver at the interconnection	42
3.14	Connection of voltmeter and ammeter to the circuit when taking voltage and current measurements respectively	42
3.15	The luminous flux measurements using FEASA Spectrometer	43
3.16	Samples for SEM scanning of (a) circuit surface at flat region (b) cold mounting of the circuit cross-section at flat and corner regions	44
3.17	The experimental setup for pull test measurements	45
3.18	The vibration test setup for LEDs joints	46
3.19	Thin surfaces applied for each part in Design Modeler	47
3.20	(a) Meshed parts configuration and (b) defined boundary conditions for the substrate	48
3.21	Ramp functions for (a) mould motion (b) plug motion and (c) inflation pressure during thermoforming simulation	49

4.1	DSC scanning for (a) PET and (b) PC materials	53
4.2	Top view of the thermoforming product (a) without the stretchable circuit and (b) with presence of the stretchable circuit	55
4.3	Stretch and thickness measurement at (a) locations for each region (b) and (c) locations for each wall surface on thermoforming product	56
4.4	The percentage of stretch at each region on top surface for the substrate without stretchable circuit	57
4.5	Starting of contact between the mould and the polycarbonate sheet	59
4.6	The percentage of stretch at each region on top surface for the substrate with stretchable circuit	59
4.7	The thickness of thermoforming product at top surfaces	60
4.8	Percentage of stretch and percentage of thickness reduction at wall surfaces of thermoforming product	62
4.9	The printed circuit on the polycarbonate sheet	63
4.10	Inside and outside corners in the thermoforming product	65
4.11	Sheet resistance before and after thermoforming process	67
4.12	The voltage readings across each LED	69
4.13	Luminous flux readings for each LED of every sample	70
4.14	Energy-dispersive X-ray spectroscopy result for the printed circuit	71
4.15	Silver particles structure and size under SEM scanning	71
4.16	SEM images for the top view of the ink at the flat region of the circuit (a) before the thermoforming and (b) after the thermoforming	73
4.17	SEM images for the side view of the ink at (a) the corner region 1 (b) the corner region 2 (c) the flat region 1 and (d) the flat region 2	74

4.18	Failed areas formation after pull test for (a) 1 st build matrix (b) 2 nd build matrix (c) 3 rd build matrix (d) 4 th build matrix (e) 5 th build matrix	76
4.19	The bonding at LED joints for (a) 1 st build matrix (b) 2 nd build matrix (c) 3 rd build matrix (d) 4 th build matrix (e) 5 th build matrix which were placed on vertical plane	77
4.20	The bonding at LED joints for (a) 1 st build matrix (b) 2 nd build matrix (c) 3 rd build matrix (d) 4 th build matrix (e) 5 th build matrix which were placed on horizontal plane	77
4.21	The x-ray scanning of bonding at each LED joint which placed in vertical position	79
4.22	The x-ray scanning of bonding at each LED joint which placed in horizontal position	80
4.23	Simulation results of (a) ASR at first region (b) ASR at second region (c) thickness at first region and (d) thickness at second region	82
4.24	Experimental results of (a) ASR and thickness at first region and (b) ASR and thickness at second region	84

LIST OF ABBREVIATION

2-D	Two-dimensional
3-D	Three-dimensional
PC	Polycarbonate
PET	Polyethylene Terephthalate
T _g	Glass Transition Temperature
T _c	Crystalline Temperature
T _m	Melting Temperature
CNT	Carbon Nanotube
FEM	Finite Element Method
SEM	Scanning Electron Microscopy
DSC	Differential Scanning Calorimetry
PCB	Printed Circuit Board
LED	Light Emitting Diode
LDS	Laser Direct Structuring
MID	Moulded Interconnect Device
PTH	Plated-Through Hole
THT	Through-Hole Technology
THD	Through-Hole Device
SMT	Surface Mount Technology
SMD	Surface Mount Device
IML	In Mould Labelling
PDMS	Polydimethylsiloxane
PI	Polyimide

ACA	Anisotropic Conductive Adhesive
ICA	Isotropic Conductive Adhesive
QFP	Quad Flat Package
PBGA	Plastic Ball Grid Array
CAD	Computer Aided Design
ASR	Area Stretch Ratio
CMM	Coordinate Measuring Machine
CNC	Computer Numerical Control
DMA	Dynamic Mechanical Analysis

**KAJIAN MENGENAI PROSES PEMBENTUKAN TERMO LITAR BOLEH
REGANG DAN PRESTASINYA DALAM PEMBUATAN LAMPU
AUTOMOTIF**

ABSTRAK

Litar tercetak telah berkembang bermula daripada papan litar tercetak ke litar fleksibel dan peranti acuan sambung (MID). Evolusi litar jenis-jenis ini adalah disebabkan oleh batasan dan permintaan yang tinggi terhadap reka bentuk litar kompleks bagi memenuhi kehendak pelanggan. Walau bagaimanapun, proses pembuatan MID memerlukan proses yang kompleks kerana melibatkan peralatan yang maju seperti mesin laser untuk menghasilkan litar tercetak di atas bahagian 3-D. Dalam kajian ini, proses pembuatan alternatif diperkenalkan untuk membina litar-litar berfungsi menggunakan dakwat boleh diregang yang dicetak pada substrat 2-D dan kemudian dijelmakan kepada bentuk 3-D melalui proses termopembentukan. Satu produk lampu bahagian belakang kereta kebangsaan dipilih sebagai produk rujukan. Acuan untuk proses pembentukan termo dibuat berdasarkan kaedah kejuruteraan terbalik yang mana dimensi bahagian lampu diukur menggunakan mesin pengukur koordinat (MPK) dan kemudian dipindahkan ke dalam lukisan 3-D menggunakan perisian Solidworks. Lukisan itu dibaca oleh mesin kawalan berangka berkomputer (KBC) melalui kod yang dihasilkan oleh pembuatan berbantu komputer (PBK) untuk menghasilkan acuan. Dakwat pada mulanya dicetak pada substrak termoplastik yang rata menggunakan teknik percetakan skrin. Dakwat tercetak dirawat di bawah 120°C selama 30 minit di dalam ketuhar untuk membentuk litar berkonduktif tinggi. Litar dengan substrat telah dijelmakan kepada bentuk 3-D melalui proses pembentukan

termo mengikut bentuk acuan yang direka serupa dengan reka bentuk lampu automotif sedia ada. Kemudian, diod pemancar cahaya (LED) dipasang pada litar dengan mendispenskan perekat konduktif pada sambungan LED dan dirawat sekali lagi pada 120°C selama 10 minit untuk membentuk ikatan yang kuat pada sambungan LED. Prestasi mekanikal dan elektrik lampu automotif reka bentuk baru dicirikan dan dibandingkan dengan reka bentuk sedia ada menggunakan peralatan seperti meter pelbagai, probe empat titik, spektrometer, mikroskop elektron pengimbas (MEP) dan mesin ujian universal. Walaupun litar reka bentuk baru telah meregang dan berubah bentuk yang membawa kepada pertambahan rintangan litar, prestasi elektriknya menunjukkan hasil yang menjanjikan. Tidak terdapat perbezaan yang ketara antara reka bentuk baru dan reka bentuk sedia ada lampu automotif dari segi penggunaan kuasa oleh sistem dan fluks bercahaya LED. Proses pembuatan litar bercetak yang baru ini menawarkan kaedah alternatif masa depan dalam pembuatan produk lampu automotif.

A STUDY ON THERMOFORMING PROCESS OF STRETCHABLE CIRCUIT AND ITS PERFORMANCE IN MANUFACTURING OF AUTOMOTIVE LIGHTING

ABSTRACT

Printed circuits have been developed started from printed circuit board to flexible circuit and moulded interconnect devices (MID). The evolution of these kinds of circuit is due to limitation and highly demand of complex circuit design to fulfil the requirements of customers. However, manufacturing process of MID requires complex process since it involves advance equipment such as laser machine to produce printed circuit on 3-D part. In this research, an alternative manufacturing process was introduced to construct functional circuits using stretchable ink printed onto 2-D substrate and then transformed into 3-D shape by thermoforming process. A rear lighting product of national car was chosen as a reference product. Mould for the thermoforming process was fabricated based on reversed engineering technique where the lighting part dimensions were measured using coordinate measuring machine (CMM) and then transferred into 3-D drawing using Solidworks. The drawing was read computer numerical control (CNC) machine through coding generated by computer aided manufacturing (CAM) to manufacture the mould. The ink was initially printed on a flat thermoplastic substrate using screen printing technique. The printed ink was cured under 120°C for 30 minutes in an oven to form a highly conductive circuit. The circuit with the substrate were transformed into 3-D shape through thermoforming process according to the shape of mould which was designed similar to the existing design of automotive lighting. Light emitting diode (LEDs) were then

assembled on the circuit by dispensing conductive adhesive at the LEDs joints and cured again in the oven at 120°C for 10 minutes to form strong bonding at the joints. Mechanical and electrical performances of the new design of automotive lighting were characterised and compared with the existing design using equipment such as multimeter, four point probes, spectrometer, scanning electron microscopy (SEM) and universal testing machine. Even the circuit of the new design had stretched and deformed that led to increase in circuit resistance, its electrical performance shows promising results. There was no significant difference between new design and existing design of automotive lightings in terms of power consumption by the system and luminous flux of LEDs. This new manufacturing process of printed circuit offers a future alternative method in manufacturing the automotive lighting product.

CHAPTER ONE

INTRODUCTION

1.1 Background

In early stage of development, conventional electronic circuits are fabricated on flat rigid boards with multiple copper patterns that interconnect the components using lead-free solder. These printed circuit boards (PCBs) offers an efficient and low cost for manufacturing process. However, there are demands to integrate electronics in 3D objects where the electronic circuits follow the surface shape of the object in order to reduce weight and material use, increase comfortability and more attractive design.

The use of LEDs in automotive lighting has become trend nowadays. The manufacturing of this LED lighting system for automotive requires certain process such as laser direct structuring (LDS) which allows 3D circuit printing. There are three primary steps included in LDS processes: (1) the polymer surface is modified by laser; (2) the laser modified specimen is activated through chemical activation; and (3) the activated specimen is plated using electroless deposition of copper (Islam et al., 2009). However, this manufacturing process is expensive and requires advance laser equipment. Since it is costly and has limitation on minimum conductive spacing of 0.3 mm for laser equipment capability, then continued efforts in research has to be done to come out an alternative process.

The advancement in materials research has contributed to introduction of stretchable materials which can be bended, stretched and twisted and it is useful for electronics field. This allows a stretchable paste printing process on polymeric substrate using surface mount technology knowledge and thermoforming process. The

stretchable electronics technology has several advantages such as allowing increased circuit density and eliminates bulky connections and wiring. Also, its assemblies may be shaped and flexible during its use (Someya, 2013).

There are many applications of the stretchable electronic circuits that has been explored by researchers such as use in medical purpose where sensor devices can be integrated directly on human body as a patch or embedded in a wearable textile (Axisa et al., 2007; Matsuhisa et al., 2015; Van Den Brand et al., 2015). Its stretchability and flexibility could accommodate any shape even it is complex.

1.2 Problem Statement

Recently, the main automotive lighting part is manufactured using moulded interconnect devices (MID) technology. This technology involves complex process since it requires advance equipment such as laser machine to produce printed circuit on 3-D part.

As alternative to MID method, stretchable printed circuit is introduced using thermoforming process to manufacture automotive lighting. However, a complete technique has not been studied to accomplish the whole process. When dealing with the thermoforming process, there are several parameters that affect the final product properties. However, behaviour of printed circuit on thermoplastic substrate is not well studied so far and additional parameters are needed to be considered in order to achieve desired product properties. Also, the application of this technique in manufacturing of an automotive lighting product requires further testing on product performances under mechanical and electrical condition.

1.3 Objective

Objectives of this research are:

1. to suggest a product concept using stretchable material as printed conductor and thermoforming process for automotive lighting application,
2. to investigate the effect of thermoforming process of automotive lighting on electrical performance of the system, and
3. to characterize the mechanical performances of thermoforming product with respect to stretchable circuit.

1.4 Scope of Work

In this work, stretchable circuit is constructed by using commercial available conductive ink through screen printing technique. One selected stretchable conductive ink is used to form a functional circuit for automotive lighting. Mechanical testing such as pull test of LED joints and vibration test follow Japanese Industrial Standard (JIS Z 3198-6) and JEDEC Standard (JESD22-B103B) respectively. All the measurements and evaluations of the new design automotive lighting are compared to performances of an available automotive lighting product (Proton Saga FLX) as a benchmark. Finite element simulation of the thermoforming process is used to visualise the behaviour of the substrate in terms of area stretch ratio and thickness after deformation according to mould shape.

1.5 Thesis Organisation

There are five chapters in this thesis. In chapter one, a brief presentation of background study, problem statement, objectives and scope of research introduced. In chapter two, literature studies on types of circuits developed in electronic industry and detailed of stretchable circuit application are presented. Methodology approach in developing a new technique in manufacturing of automotive lighting has been highlighted in chapter three. In chapter four, effects of thermoforming process on stretchable circuit and thermoforming product performance are discussed in detail. Finally, conclusion and recommendations for future work is pointed out in chapter five.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Printed circuit design development starting from printed circuit board (PCB) to flexible circuit and then moulded interconnect device (MID) occurs due limitation of previous design and high demands towards a more complex design of circuit to accommodate the part shape in certain application. The latest circuit design tends to complement the previous circuit design in order to fulfil the requirements.

Currently, requirement for 3-D circuit in many industries such as automotive and telecommunication has encouraged further research in 3-D circuit. Advance in material has introduced stretchable ink to be used for printed circuit on thermoplastic substrate where thermoforming process is needed to transform the circuit from 2-D to 3-D. Consideration on substrate material, circuit printing technique and thermoforming parameters are necessary in order to apply stretchable circuit in the thermoforming process.

2.2 Evolution of Circuit Design

Circuit design started with printed circuit board (PCB) that replaced all mechanical wiring bonding. Then, flexible circuit was developed at which a part of the circuit board could be bent instead of all rigid body. Currently, moulded interconnect device (MID) had been implemented in automotive and telecommunication industries.

2.2.1 Printed Circuit Board (PCB)

PCB is a substrate of a paper or glass fabric impregnated with a resin, usually epoxy, phenolic or silicone (Brindley, 1990). There are two types of boards that are typically used which are single-sided boards and double-sided boards. Single-sided boards are used when minimum cost is concerned but when the numbers of components or jumper wires are too many, double-sided boards are considered. It can be with or without plated-through hole (PTH). In order to choose which boards to be used, PCB area to component area ratio should be considered as follows:

Table 2.1: PCB to component area ratio (Leonida, 1989).

Board Type	Single-sided	Double-sided PTH
Discrete components (ICs not more than 5% of the area)	2-3	1.5-2
Mixed (ICs from 35% to 50%)	2.5-4	2-3
IC board (discrete components not more than 20%)	4-6	2-3

The electronic components are assembled on the circuit boards by two ways: through-hole technology (THT) using through-hole devices (THDs) and surface-mount technology (SMT) using surface-mount devices (SMDs) as illustrated in Figure 2.1.

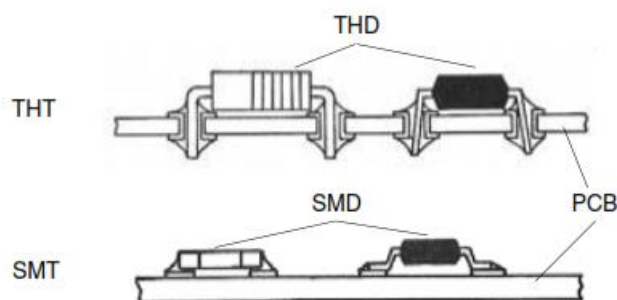


Figure 2.1: Assembly principles of THT and SMT (Coombs, 2008).